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the same inclination of clamping reinforcement (refer to Fig. 5). The second is the relatively very high concrete strength.

The discusser expressed interest in further information to be able to check the results presented in Table 1. This information is provided in Table A1, as referenced in the footnote on page 422 of the paper. The author will gladly supply the discusser with the detailed database upon request via e-mail at khaldoun.rahal@ku.edu.kw.

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Strengthening of Flat Slabs against Punching Shear Using Post-Installed Shear Reinforcement. Paper by Miguel Fernández Ruiz, Aurelio Muttoni, and Jakob Kunz

Discussion by Andor Windisch

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The authors apply the critical shear-crack theory for an innovative method for the strengthening of flat slabs.

Looking at Fig. 3(b), it seems that deformed bars were certainly used for the shear reinforcement. Please confirm.

The rate of the shear reinforcement is characterized by ρ_w (refer to Eq. (2)). Looking at Fig. 8 with the (very informative) cracking patterns after they are saw cut, the question arises whether it would be more realistic to take into account the number of stirrups crossing the failure crack instead of calculating with the smeared stirrups. As a matter of fact, in Eq. (7), ΣA_{swi} is defined as the cross-sectional area of the shear reinforcement; it could be read as a reference to the number of shear reinforcing bars. Moreover, the reference to the stress in the shear reinforcement $\sigma_{si}(\psi)$ in Eq. (7) and the proposed equation for determining its value (refer to Eq. (9)) reveals that not all of these can refer to smeared stirrups.

In eliminating the smeared stirrups, another questionable parameter could disappear, too: b_0, the length of the control perimeter. In the case of the critical shear-crack theory, this parameter loses its justification; in the case of the different s_0 distances (refer to Fig. 5 and 8), the "control perimeters" are certainly different, too.

The three different types of flexural reinforcement—hot-rolled or cold-worked with different bond characteristics and two considerably different levels of yield strength and probably different bond characteristics, too—should be taken into account when evaluating the test results. The identical ρ = 1.50% geometrical rates of flexural reinforcement for Slabs PV1 to PV3 and Slabs PV14 to PV17 should result in quite different behaviors of the specimens (the varying concrete strengths diversify these even further). Hence, the mechanical rate of flexural reinforcement could be a better parameter.

Comparing the V_{test} values of Slabs PV6 to PV8, the deceptive character of the smeared shear reinforcement ratio ρ_w can be perceived. Slab PV8 had half the ρ_w value of Slabs PV6 and PV7; nevertheless, the strength was identical.

While discussing the failure patterns of Slabs PV14 and PV15 with heavy shear reinforcement, the authors refer to crushing of the compression strut. The following questions/remarks arise:

- Are the compression strut and the critical shear-crack model compatible with each other at all?
- The position of the critical shear crack is quite different in the case of Slab PV14 from Slab PV15. Where is the compression strut situated in these two cases?
- Slabs PV2 and PV3 have the same ρ values as Slabs PV14 and PV15; nevertheless, even if at dimensioning, flexure and shear are treated independently from one another per their definitions. The compression zone must also fail along the critical shear crack at failure.
- The authors explain that the larger strength of Slab PV14 "was due to the fact that anchorages of the shear reinforcement were placed beyond those of Slab PV15, leading to more limited stress concentrations in the compression-critical region." Please clarify—how does the "more limited stress concentration in the compression-critical region" let the shear strength increase? The shapes of the failure sections of Slabs PV1, PV2, PV7, PV8, PV14, PV16, PV17, and PV19 shown in Fig. 8 are identical—where can the "more limited stress concentrations" be identified?
- The discusser means that the "failure of the compression strut" is in fact a critical shear crack running quite vertical around the column, scarcely intersecting the bars of the shear reinforcement. Increasing s_0 (refer to Fig. 5(a)) also increases the probability of this type of failure.

The authors detect "progressive smearing" of the cracks at the column region as the amount of shear reinforcement increases. It is obvious that increasing tensile reinforcement in any reinforced concrete member in tension decreases the crack distances—this is never understood as "smearing."

How do the bond stresses along the different bars of the shear reinforcement develop/change when successive cracks do occur with increased loading? Compare the first inclined bars near the column (for example, in Slabs PV8, PV14, and PV15). Is a pullout at the upper bond anchorages of the shear bars possible or was it detected at one of the slabs?

Based on Eq. (1), (9), and (10), the bond length of the shear reinforcing bars, the opening of the critical shear crack at the level of the shear reinforcement, and the rotation of the slab necessary for the yielding of the 16 mm (0.63 in.) shear reinforcement can be calculated. The necessary bond length is approximately 100 mm (3.94 in.). The necessary crack width at the intersection of the shear reinforcement is approximately 0.25 mm (0.1 in.). Please note that this crack width is far below the allowable crack widths, as stated in the serviceability limits. The necessary rotation ψ in the case of the intersection at a height of 120 mm (4.7 in.) is 0.41%. In the case of a thicker flat slab, the intersection could be at approximately 250 mm (10 in.); here, beyond ψ = 0.2%, the shear reinforcement yields, according to the equations given by the authors. The courses of the load-rotation curves given in Fig. 6 and the ψ_{test} values achieved at failure given in Table 1 fully contradict these calculated values.

It would be interesting to learn how Eq. (7) to (11) were applied to calculate V_{calc}. The accuracy of how the rotation of the slab was determined does not seem to influence the accuracy of the calculated shear force. Examining the conjugated V_{test}/V_{calc} and ψ_{test}/ψ_{calc} values given in Table 1, it can be detected that there is absolutely no interdependence between these pairs of values. The trendline's equation is

$$(V_{test}/V_{calc}) = -0.0006(\psi_{test}/\psi_{calc}) + 1.07$$

with $R^2 = 2 \times 10^{-5}$.

This could indicate that the rotation ψ is not a very strong variable. In the case of Slabs PV3 and PV15, the ψ_{test}/ψ_{calc} values are significantly greater than 1; nevertheless, the calculated shear strength is fairly near the measured value. Please comment.

Equation (13) yields the so-called crushing strength of compression struts $\lambda \cdot V_{R,c}$, where $\lambda > 1$. It is not clear why the width of the critical shear crack ($\propto \psi \cdot d$) should have any influence on the strength of the "concrete strut" that is situated between the column and this crack. Furthermore, why does the crushing strength depend on $\sqrt{f_c}$ and not directly on f_c, and why does it depend on the aggregate interlock?

Even if the model assumptions were correct, the influence of some important parameters—such as slab thickness and the maximum size of the aggregate—cannot be validated, as these were not varied for this test series.

Referring to Fig. 9(b), the authors state that "as rotations increase by addition of shear reinforcement, the concrete contribution diminishes." Neither the test results nor the current view in the field concerning the source of the concrete shear contribution—that is, the aggregate interlock—validate this statement: we all agree that additional shear reinforcement decreases the width of shear cracks (even that of the critical shear crack). This fact supports the impression that was already predicted by the discusser regarding a previous paper[6]; the rotation of the slab ψ is definitely not the appropriate fundamental parameter of the phenomenon.

The coefficient of variation of V_{test}/V_{calc} is very small compared to the coefficient of variation of the basic parameter of the model ψ_{test}/ψ_{calc}, which is quite high.

AUTHORS' CLOSURE

The authors would like to thank the discusser for his interest in the paper and in the critical shear crack theory (CSCT). Detailed replies to his questions are given in the following:

- As shown in Fig. 3(b), deformed bars were used. This is obvious, as the best bond conditions were sought.
- The shear reinforcement ratio ρ_w was selected as the best representative parameter to compare different reinforcement configurations—not a stepwise function, such as the one suggested by the discusser.
- The same type of steel (hot-rolled or cold-worked) was used for the same flexural reinforcement ratio. The differences in the yield strength were accounted for by the load-rotation behavior of the specimens according to Reference 6 (it can be noted that the CSCT is based on a rational mechanical model and allows the consideration of such influences).
- The explanation for the measured strength of Slab PV8 is discussed in Fig. 11(c). Failure was governed by bending strength (yield-line mechanism) and not by shear strength. The deformation capacity nevertheless increased as more shear reinforcement was used (in accordance with the CSCT predictions).
- Details regarding the crushing strength according to the CSCT can be found in Reference 8.
- Significant cracking developed in the region of the compression strut for Slabs PV14 and PV15 (refer to Fig. 8).
- Slab PV2 failed slightly differently (pullout of anchorages) and Slab PV3 failed outside the shear-reinforced zone. Both failure modes are explained in depth in the paper.
- To install the bars, holes have to be drilled in the specimens. This disturbs the struts in the soffit (the compression side of the slab) if the holes are too close. This explains the behavior of Slab PV15.
- In the authors' opinion, the term "smearing" is correct.
- Shear reinforcement is activated on the top of the specimen only by bond. Measurements on the strains of the bar (not detailed within the paper) taken at the HILT-Schaan Laboratory confirmed this.
- If the discusser finds a contradiction, he has probably made a mistake in his calculations (perhaps in the load-rotation curve—the calculations of the discusser are not detailed and cannot be checked). Please refer to Table 1 for comparisons of ψ_{calc} (a very good agreement was observed). More comparisons can be found in Reference 8.
- Rotation is indeed a very good variable to calculate the punching shear strength.[6,8] For members with shear reinforcement, however, it leads to some scatter, as rotations may increase at failure (especially for members with large amounts of shear reinforcement, such as Slabs PV3, PV14, and PV15). This increase in the deformation capacity is neglected (on the safe side) with the proposed approach and leads to practically no difference in the estimate of the strength.
- Details regarding the approach for calculating crushing strength can be found elsewhere.[8] The authors have validated this approach (including size and strain effect) with a specific test campaign in another paper submitted to this journal, which is currently under peer review.
- The authors respect the discusser's opinion on the pertinence of the rotation as a key parameter but do not share it. It has been validated through extensive research and detailed measurements.[6,8] It is a physical parameter, clearly explaining how this or any other shear reinforcement system works and how to design it. It also leads to an excellent understanding of the mechanics of members without shear reinforcement and allows very accurate strength predictions.[6] It accounts for the various mechanical and geometrical parameters as well as the reinforcing procedure (post-installing and rotations at the time of prestressing). It constitutes the current state of knowledge (the design method included in the first complete draft of the new Model Code 2010). More refinements can (and probably will) be included, but for the time being, it is, in the authors' opinion, the best physical approach to the problem.